

# Deuteron form factors in a phenomenological approach

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The electromagnetic form factors of the deuteron, particularly the quadrupole form factor, are studied with a help of a phenomenological Lagrangian approach where the vertex of the deuteron-proton-neutron with  $D$ -state contribution is explicitly taken into account. The result shows the importance of this contribution to the quadrupole form factor in the approach.

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## I. INTRODUCTION

The study of electromagnetic form factors of nucleon and light nuclei, like deuteron and He-3, are crucial for the understanding of the nucleon structures. Deuteron, as the most simplest nuclei, has been a subject of many years (for some recent reviews[1–4]). Since it is a weekly bound state of the proton and neutron, the study of the deuteron can shed light on the study of the nucleon as well as on the nuclear effects. Moreover, as a spin-1 particle, the deuteron structures are different from the spin-1/2 nucleon and He-3, and from the spinless pion meson. There are many discussions on the deuteron structures, like its wave functions, binding energy, the electromagnetic form factors, and the parton distributions, in the literature. Those works are usually based on the phenomenological potential models with quark, meson, and nucleon degrees of freedom and based on some effective field theories etc. [1–12]. The realistic deuteron wave functions, with the help of meson exchange potential model, have been explicitly given by Refs. [13–15].

In our previous works [16, 17], a phenomenological Lagrangian approach is applied for the electromagnetic form factors of the deuteron, where it is regarded as a loosely bound state of a proton and a neutron, and the two constituents are in relative  $S$ -wave for simplicity. The coupling of the deuteron to its two composite particles is determined by the known compositeness condition from Weinberg [18], Salam [19] and others [20, 21]. Our phenomenological effective Lagrangian approach has been proven to be successful in the study the weekly bound state problems, like the new resonances of  $X(3872)$ , and  $\Lambda_c^+(2940)$ , the EM form factors of pion as well as some other observables [22, 23].

It should be stressed that since only one-body  $S$ - wave operator contribution is considered in our previous study [16], the estimated quadrupole moment of the deuteron is negligibly small when compared to data. According to the non-relativistic potential model calculation [13], one sees that the deuteron quadrupole moment is very sensitive to the  $D$ - wave component of the deuteron. Therefore,  $S$ - state contribution is not sufficient. In order to avoid the discrepancy, several two-body arbitrary and phenomenological Lagrangians were introduced, by hand, to compensate the discrepancy [16].

The purpose of this work is to re-study the deuteron electromagnetic form factors with the phenomenological approach. Here both the  $S$ - and  $D$ - state contributions to the vertex of the deuteron-proton-neutron are simultaneously taken into. It is expected that by considering the  $D$ - state contribution in the vertex, the estimated deuteron quadrupole could be sizeably improved. This paper is organized as follows. Section 2 briefly shows our theoretical framework, particularly the  $D$ - state contribution to the vertex. Numerical results and some discussions are given in section 3.

## II. FRAMEWORK OF THE APPROACH

Deuteron, as a spin-1 particle, has three independent form factors. The matrix element for electron-deuteron (ED) elastic scattering, as shown in Fig. 1, can be written as

$$\mathcal{M} = \frac{e^2}{Q^2} \bar{u}_e(k') \gamma_\mu u_e(k) \mathcal{J}_\mu^D(P, P'), \quad (1)$$

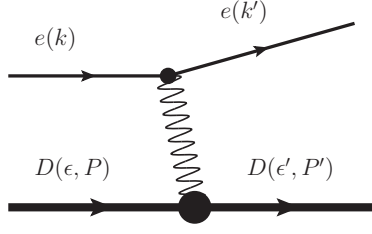


FIG. 1: Electron-deuteron scattering

under the one-photon exchange approximation. In eq. (1)  $k$  and  $k'$  are the four-momenta of initial and final electrons and  $\mathcal{J}_\mu^D(P, P')$  stand for the deuteron EM current. Its general form is

$$\begin{aligned} \mathcal{J}_\mu^D(P, P') = & \\ & - \left( G_1(Q^2) \epsilon'^* \cdot \epsilon - \frac{G_3(Q^2)}{2M_d^2} \epsilon \cdot q \epsilon'^* \cdot q \right) (P + P')_\mu \\ & - G_2(Q^2) \left( \epsilon_\mu \epsilon'^* \cdot q - \epsilon'_\mu \epsilon \cdot q \right), \end{aligned} \quad (2)$$

where  $M_d$  is the deuteron mass,  $\epsilon(\epsilon')$  and  $P(P')$  are polarization and four-momentum of the initial (final) deuteron, and  $Q^2 = -q^2$  is momentum transfer square with  $q = P' - P$ . The three EM form factors  $G_{1,2,3}$  of the deuteron are related to the charge  $G_C$ , magnetic  $G_M$ , and quadrupole  $G_Q$  form factors by

$$\begin{aligned} G_C &= G_1 + \frac{2}{3} \tau G_Q, \quad G_M = G_2, \\ G_Q &= G_1 - G_2 + (1 + \tau) G_3, \end{aligned} \quad (3)$$

with the factor of  $\tau = Q^2/4M_d^2$ . These three form factors are normalized at zero recoil ( $Q^2 = 0$ ) as

$$\begin{aligned} G_C(0) &= 1, \quad G_Q(0) = M_d^2 \mathcal{Q}_d = 25.83, \\ G_M(0) &= \frac{M_d}{M_N} \mu_d = 1.714, \end{aligned} \quad (4)$$

where  $M_N$  is the nucleon mass,  $\mathcal{Q}_d$  and  $\mu_d$  are the quadrupole and magnetic moments of the deuteron.

The unpolarized differential cross section for the  $eD$  elastic scattering can be expressed by the two structure functions,  $A(Q^2)$  and  $B(Q^2)$ , as

$$\frac{d\sigma}{d\Omega} = \sigma_M \left[ A(Q^2) + B(Q^2) \tan^2 \left( \frac{\theta}{2} \right) \right], \quad (5)$$

where  $\sigma_M = \alpha^2 E' \cos^2(\theta/2)/[4E^3 \sin^4(\theta/2)]$  is the Mott cross section for point-like particle,  $E$  and  $E'$  are the incident and final electron energies,  $\theta$  is the electron scattering angle,  $Q^2 = 4EE' \sin^2(\theta/2)$ , and  $\alpha = e^2/4\pi = 1/137$  is the fine-structure constant. The two form factors  $A(Q^2)$  and  $B(Q^2)$  are related to the three EM form factors of the deuteron as

$$\begin{aligned} A(Q^2) &= G_C^2(Q^2) + \frac{8}{9} \tau^2 G_Q^2(Q^2) + \frac{2}{3} \tau G_M^2(Q^2) \\ B(Q^2) &= \frac{4}{3} \tau (1 + \tau) G_M^2(Q^2). \end{aligned} \quad (6)$$

Clearly, the three form factors  $G_{C,M,Q}$  cannot be simply determined by measuring the unpolarized elastic  $eD$  differential cross section. To uniquely determine the three form factors of the deuteron one additional polarization variable is necessary. For example, one may take the polarization of  $T_{20}$  [1].

Take an assumption that the deuteron as a hadronic molecule—a weakly bound state of the proton and neutron, one may simply write a phenomenological effective Lagrangian of the deuteron and its two constituents of the proton and neutron as

$$\mathcal{L}_D(x) = g_D D_\mu(x) \int dy \Phi_D(y^2) \bar{p}(x + y/2) \Gamma_D^\mu C \bar{n}^T(x - y/2) + H.c., \quad (7)$$

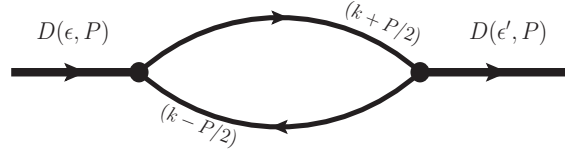


FIG. 2: The mass operator of the deuteron

where  $D_\mu$  is the deuteron field,  $C\bar{n}^T(x) = n^c(x)$ , and  $C = i\gamma^2\gamma^0$  denotes the matrix of charge conjugation, and  $x$  is the centre-of-mass (C. M.) coordinate. In the above equation  $\Gamma_D^\mu$  is the vertex for the deuteron-proton-neutron and the correlation function  $\Phi_D(y^2)$  characterizes the finite size of the deuteron as a  $pn$  bound state. The correlation function  $\Phi_D(y^2)$  depends on the relative Jacobi coordinate  $y$ .

If only the  $S$ - wave contribution is considered, the simplest form of the vertex is  $\Gamma_D^\mu \sim \gamma^\mu$  which has been employed before [16]. When both the  $S$ - and  $D$ - states contributions are considered, then the vertex becomes more complicated. According to the work of Blankenbecler, Gloderber, and Halpern [24] the vertex of the deuteron-proton-neutron is

$$\Gamma_D^\mu = \Gamma_D^{1,\mu} + \Gamma_D^{2,\mu} \quad (8)$$

where the first and second terms stands for the contribution from  $S$ - and  $D$ - states, respectively. They are

$$\Gamma_D^{1,\mu} = \frac{1}{2\sqrt{2}} \left( 1 + \frac{P}{M_d} \right) \gamma^\mu \quad (9)$$

and

$$\Gamma_D^{2,\mu} = \frac{\rho}{16} \left( 1 + \frac{P}{M_d} \right) \left( \gamma^\mu - \frac{3}{k^2} \not{k} \gamma^\mu \not{k} \right) \quad (10)$$

with  $\rho$  being a measure of the  $D$ -state admixture,  $k$  is the relative momentum between the proton and neutron, and  $k^2 = M_N \delta$  with  $\delta$  being the binding energy of the deuteron as shown in Fig. 2. Here, it should be mentioned that in the rest frame of the deuteron, the non-relativistic reduction gives

$$\epsilon_i \Gamma_D^{1,i} C = -\frac{i}{\sqrt{2}} \vec{\sigma} \cdot \vec{\epsilon} \sigma_2 = \begin{pmatrix} \epsilon_{-1} & -\frac{1}{\sqrt{2}} \epsilon_z \\ -\frac{1}{\sqrt{2}} \epsilon_z & \epsilon_{+1} \end{pmatrix}. \quad (11)$$

It means a combination of two spin-1/2 states, proton and neutron, forms a spin triplet state. Similarly, in the non-relativistic limit,  $\left( \gamma^\mu - \frac{3}{k^2} \not{k} \gamma^\mu \not{k} \right)$  means the proton and neutron couple to spin triplet state and this spin triplet state re-couples  $Y_{2m_i}(\hat{k})$  to form a state with the same quantum numbers of the deuteron.

The coupling of the deuteron to its two constituents,  $g_D$  in eq. (7) is determined by the known compositeness condition  $Z = 0$  proposed by Weinberg, Salam and others [18–21]. This condition implies that the probability to find a proton and neutron system inside the deuteron is unity. Thus, the coupling of  $g_D$  is determined according to  $Z_D = 1 - \Sigma'_D(M_D^2) = 0$ , with

$$\Sigma'_D(M_D^2) = g_D^2 \Sigma'_{D\perp}(M_D^2) \quad (12)$$

being the derivative of the transverse part of the mass operator (see Fig. 2). Usually, the mass operator splits into the transverse and longitudinal parts of  $\Sigma_D^{\alpha\beta}(k) = g_\perp^{\alpha\beta} \Sigma_{D\perp}(k^2) + \frac{k^\alpha k^\beta}{k^2} \Sigma_{D\parallel}(k^2)$ , with  $g_\perp^{\alpha\beta} = g^{\alpha\beta} - k^\alpha k^\beta / k^2$  and  $g_\perp^{\alpha\beta} k_\alpha = 0$ . We see that the coupling of the deuteron to its constituents of the proton and neutron,  $g_D$ , is well determined by the compositeness condition.

A basic requirement for the choice of an explicit form of this correlation function is that its Fourier transform vanishes sufficiently fast in the ultraviolet region of Euclidean space to render the Feynman diagrams ultraviolet finite. Usually a Gaussian-type function is selected as the correlation for simplicity. One may choose  $\tilde{\Phi}_D(k^2) = \exp(-k_E^2/\Lambda^2)$  for the Fourier transform of the correlation function, where  $k_E$  is the Euclidean Jacobi relative momentum and  $\Lambda$  stands for the free size-parameter which represents the distribution of the constituents in the deuteron.

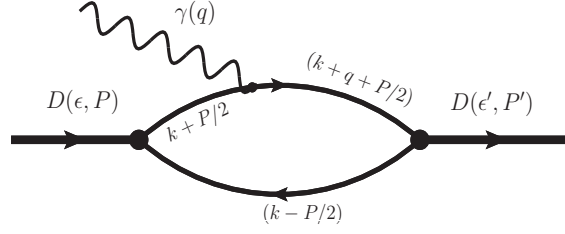


FIG. 3: Photon-deuteron interaction

Here the analytical expression for the coupling is

$$\frac{1}{g_D^2} = \Sigma'_{D\perp,1} + \rho \Sigma'_{D\perp,2}, \quad (13)$$

where  $\Sigma'_{D\perp,1}$  and  $\Sigma'_{D\perp,2}$  stand for the derivatives of the transverse parts of the mass operator from the contributions of the  $S$ - and  $D$ - states, respectively. The explicit expressions are

$$\begin{aligned} \Sigma'_{D\perp,1} = & \frac{1}{32\pi^2} \int \frac{d\alpha d\beta}{Z_0^3} \times \left\{ \frac{A(\alpha, \beta)}{Z_0} \left[ 1 + \frac{\Lambda_S^2}{4M_d^2 Z_0} \right] \right. \\ & + \frac{B(\alpha, \beta)}{2} \times \left[ \mu_d^2 \left( 1 + \frac{A(\alpha, \beta)}{Z_0^2} \left( 1 + \frac{\Lambda_S^2}{4M_d^2 Z_0} \right) \right) + \frac{3\Lambda_S^2}{2M_d^2 Z_0^2} - \frac{1}{4Z_0} \right] \Big\} \\ & \times \exp \left[ -2(\alpha + \beta) \mu_N^2 + \frac{A(\alpha, \beta)}{2Z_0} \mu_d^2 \right] \end{aligned} \quad (14)$$

where  $\mu_{N,d} = M_{N,d}^2 / \Lambda_S^2$  and

$$\begin{aligned} A(\alpha, \beta) &= (1 + 2\alpha)(1 + 2\beta) \\ B(\alpha, \beta) &= \alpha + \beta + 4\alpha\beta \\ Z_0 &= 1 + \alpha + \beta, \end{aligned} \quad (15)$$

and

$$\begin{aligned} \Sigma'_{D\perp,2} = & \int \frac{d\alpha d\beta}{16\sqrt{2}\pi^2 Z_1^3} \times \left\{ \frac{A'(\alpha, \beta)}{Z_1} \left[ 1 + \frac{3\Lambda_S^2}{8\delta M_D Z_1} \right] \right. \\ & + \frac{B'(\alpha, \beta)}{2} \left[ \mu_d^2 \left( 1 + \frac{A'(\alpha, \beta)}{Z_1^2} \left( 1 + \frac{3\Lambda_S^2}{8\delta M_D Z_1} \right) \right) + \frac{1}{2Z_1^2} \left( 1 - \frac{15M_d}{8\delta} + \frac{9\Lambda_S^2}{2\delta M_d} \right) \right] \Big\} \\ & \times \exp \left[ -2(\alpha + \beta) \mu_N^2 + \frac{A'(\alpha, \beta)}{2Z_1} \mu_d^2 \right] \end{aligned} \quad (16)$$

with

$$\begin{aligned} A'(\alpha, \beta) &= \left( \frac{1 + a_{SD}}{2} + 2\alpha \right) \left( \frac{1 + a_{SD}}{2} + 2\beta \right) \\ B'(\alpha, \beta) &= \frac{1 + a_{SD}}{2} (\alpha + \beta) + 4\alpha\beta \\ Z_0 &= \frac{1 + a_{SD}}{2} + \alpha + \beta, \end{aligned} \quad (17)$$

and  $a_{SD} = \Lambda_S^2 / \Lambda_D^2$ . Here we simply ignore the  $\rho^2$ - dependent term since  $\rho$  is expected to be small, and we consider that the correlation functions of the  $S$ - and  $D$ - states are not necessarily the same, therefore we have totally three parameters  $\Lambda_S$ ,  $\Lambda_D$  and  $\rho$  in this calculation. Then, we can calculate the matrix element of photon-deuteron

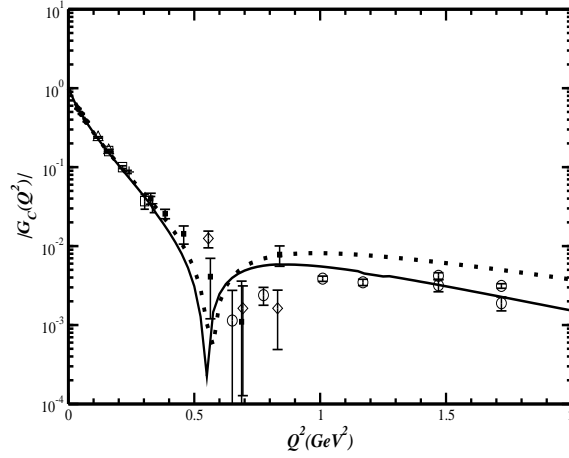


FIG. 4: Estimated deuteron charge form factor  $G_c(Q^2)$ . The solid and dotted curves are the results of our calculations and of the phenomenological parametrization[28]. The data are open circle[29], open square[30], open diamond[31], plus[32], triangle up[33], filled circle[34], and filled square[35], respectively.

interaction as shown in Fig. 3. We have

$$\begin{aligned} \mathcal{M}^\mu = & \sum_{(N=p,n)} \sum_{(i,j=1,2)} \int \frac{d^4k}{(2\pi)^4} g_D^2 \epsilon'_\alpha \epsilon_\beta \times Tr \left[ \frac{\Gamma_D^{i,\alpha}(\not{k} + \not{q} + \not{p}/2 + M_N)}{(k+q+p/2)^2 - M_N^2} \right. \\ & \cdot \frac{\Gamma_{\gamma N}^\mu(\not{k} + \not{p}/2 + M_N)}{(k+p/2)^2 - M_N^2} \cdot \frac{\Gamma_D^{j,\beta}(\not{k} - \not{p}/2 - M_N)}{(k-p/2)^2 - M_N^2} \Big] \\ & \times exp \left[ -k_E^2/\Lambda_j^2 - (k+q/2)_E^2/\Lambda_i^2 \right] \end{aligned} \quad (18)$$

where the photon-nucleon current of

$$\Gamma_{\gamma N}^\mu = F_{1,N}(Q^2)\gamma^\mu + F_{2,N}(Q^2)\frac{i\sigma^{\mu\nu}q_\nu}{2M_N} \quad (19)$$

is employed with  $F_{1,N}$  and  $F_{2,N}$  being the known nucleon Dirac and Pauli form factors and  $N = p, n$ , stand for the proton and neutron, respectively.

### III. NUMERICAL RESULTS AND DISCUSSIONS

We calculate the matrix element of eq. (18) and consider the one-photon exchange approximation for the photon-deuteron current as shown eq. (1). Thus we can get the corresponding deuteron three form factors  $G_{1,2,3}$  as well as the deuteron charge  $G_c(Q^2)$ , magnetic  $G_M(Q^2)$  and quadrupole  $G_Q(Q^2)$  form factors. There are some parameterizations for the nucleon form factors of  $F_{1,2}(Q^2)$  in the literature for the proton and neutron by [25–27]. In the present calculation, we employ the ones of Blunden [27]. The three model-dependent parameters,  $\Lambda_S = 0.10 \text{ GeV}$ ,  $\Lambda_D = 0.08 \text{ GeV}$  and  $\rho = 0.03$ , are fixed by fitting to the experimental data. The obtained charge, magnetic and quadrupole form factors are shown in Figs. (4-6).

It should be stressed that, in this work according to the discussions of Ref. [24], we explicitly include the  $D$ -state contribution to the deuteron-proton-neutron vertex as shown in eq. (10). Comparing to our previous work in [16], we found that this contribution is very important for the understanding of the quadrupole moment and quadrupole form factors. The estimated  $G_M(0)$  and  $G_Q(0)$  are about 1.53 and 21.38, respectively. These two values are reasonable comparing to the normalization conditions of 1.714, and 25.83 given in eq. (4). If we only take the  $S$ -wave contribution into account, we hardly reproduce the experimental measurement for the quadrupole moment

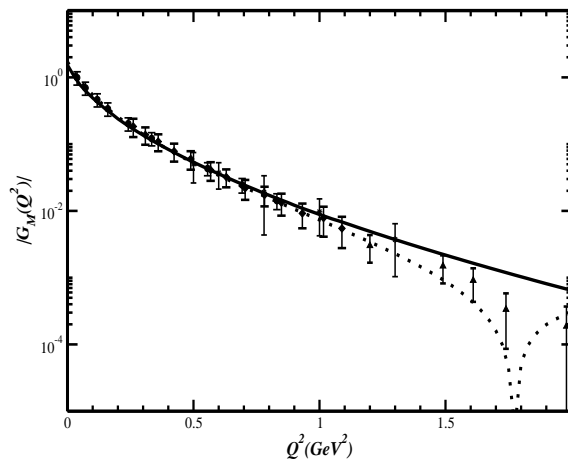


FIG. 5: Estimated deuteron magnetic form factor  $G_M(Q^2)$ . The solid and dotted curves are the results of our calculations and of the phenomenological parametrization[28]. The data are circle[36], square[37], diamond[38], and triangle[39], respectively.

at the zero-recoil limit, although the estimated magnetic moment is consistent with the data. Here, the negligibly small value of the quadrupole moment in Ref. [16] is improved due to the inclusion of the  $D$ -state contribution. Meanwhile, the charge and magnetic moments also remain reasonably.

In summary, we explicitly consider, in this work, the  $D$ -state contribution to the vertex of the deuteron-proton-neutron, as well as the  $S$ -wave one simultaneously, and find that our four-dimensional phenomenological Lagrangian approach can reasonably reproduce the deuteron charge, magnetic, particularly, quadrupole form factors simultaneously. The estimated quadrupole moment is much improved due to the inclusion of the  $D$ -state contribution. It should be stressed that our present approach is a fully relativistic and it is different from the potential model calculations based on the three-dimensional framework.

Of course, the present calculation can be further improved, since we still cannot reproduce correctly the crossing point of the charge and magnetic form factors of the deuteron as discussed in Ref. [28]. It is found that the experimental data for  $G_C$  and  $G_M$  show the existence of a zero, for  $Q_{0C}^2 = 0.7 \text{ GeV}^2$  and  $Q_{0M}^2 = 2 \text{ GeV}^2$ , respectively. This is probably due to the fact that our selected correlation functions are still simple. Moreover, the explicit form of the  $D$ -state contribution, as shown in eq. (10), is not unique [14]. A more sophisticated calculation is in progress. Finally, it is expected that the future calculation of the deuteron generalized parton distribution functions with help of this approach is promising.

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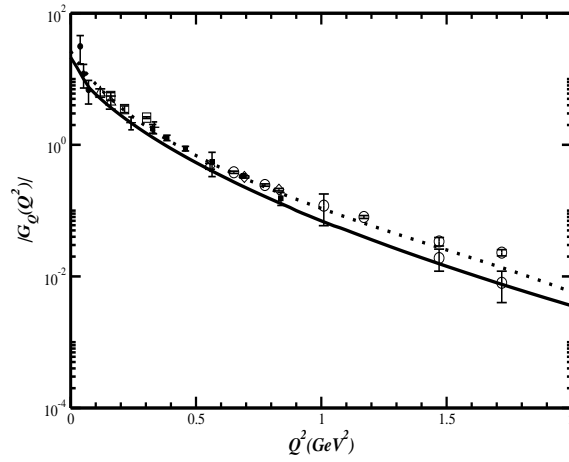


FIG. 6: Estimated deuteron quadrupole form factor  $G_Q(Q^2)$ . Notations are the same as Fig.4.

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